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Biosolids recycling: A proposed methodology for the assessment of the impact on groundwater

Groundwater Management Programme

Commissioned Report CR/05/123N

BRITISH GEOLOGICAL SURVEY

GROUNDWATER MANAGEMENT PROGRAMME

COMMISSIONED REPORT CR/05/123N

Biosolids recycling: A proposed methodology for the assessment of the impact on groundwater

N S Robins

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1 Introduction

A groundwater risk assessment protocol is needed for land restoration schemes using recycled biosolids. A hydrogeological risk assessment for the Darnconner site in East Ayrshire [NS5723 to NS5823] has been used as a case study to develop the protocol. The proposed outline for developing the protocol included the following components:

1. Gather available geological information for the site and environs from 1: 50 000 scale geological maps and more detailed information where available.
2. Interrogate the BGS borehole database (Wellmaster) to establish existing groundwater users in the vicinity and available information regarding depth to water, water quality, etc.
3. Identify the catchment Baseflow Index (HOST) to establish the degree to which surface water courses are groundwater dependent.
4. Bring the three strands of information together to create a preliminary conceptual groundwater flow model for the vicinity of the site. This is presented as a three dimensional schematic supported by cross sections if details are available.
5. Identify pathways from the site to the water table, such as former adits, local faulting etc., in addition to likelihood of any intergranular ingress.
6. Access BGS HiRES airborne geophysics images to see if existing pollution plumes derive from or cut across the recycling sites.
7. Evaluate the potential risk to groundwater from the site and likely flow path any contaminated groundwater may take, including emergence to surface water.
8. Advise on any further work that may be required, e.g. drilling and monitoring.

The time estimate for each assessment was aimed at four man days (including Coal Authority input to access mine abandonment plans for former collieries in the vicinity, and time for accessing the HiRES data where appropriate, to evaluate pollution egress from treated sites), plus the walkover site of all four sites, a further one day.

Bacteria are largely attached to soil particles, are not easily mobile and die-off is rapid in the soil profile. Bacterial risk to groundwater is, therefore, low unless there is direct transport from the soil via a fracture or existing mine adit to the water table. The risk from metal contamination of groundwater is also low as metals are bound to the sludge organic matter and the receiving soil provided the pH is maintained at a near neutral environment. The main potential pollution risk from biosolids is nitrate derived from the oxidation of ammonium and nitrite species leaching from the topsoil. Risk assessment hinges on the potential for transport of nitrogen species to groundwater. A scorecard system to assess the nature of the pathway and its potential to transport nitrogen rich infiltration to the water table is presented.

The use of sewage sludge as a primer for vegetative growth and as a humic foundation for soil development at mine sites is not new. It was common practice in the 1980s and 1990s to mix biosolids with the more shaley rock wastes from colliery and opencast sites to attempt to recreate a soil cover. The technique was, for example, applied repeatedly and successfully during post-closure procedures of numerous opencast sites in South Wales. There are no recorded instances of bacterial, metal or nitrogen contamination of local groundwaters, although background levels of all three potential contaminant groups were likely to have been elevated during the initial post-closure period due to intensive mining and industrial activity taking place at that time. Detailed descriptions of this work may be available in the records of the Coal Authority at Mansfield, but there is otherwise little reliable information reported in the open literature. Biosolids were also used at a number of Scottish reclamation sites including Heathland Forest (Bye Law Hill) near Forth (see Section 4).

2 Hydrogeological prognosis of the Coal Measures at Darnconner

The Coal Measures are characterised by a cyclical sequence of sandstones, siltstones, mudstones and shales, seatearths and coals. The mean permeability of the sandstones is of the order of 10^{-2} m d^{-1} but it is less in the other lithologies. The dominant flow and storage mechanism is within available fractures. Fracturing is enhanced in the vicinity of faults, and other tectonic features and may be created by mining settlement or slumping of bedrock towards deep opencast pits. Typical borehole yields in the Coal Measures are 2 to 4 l s^{-1}, exceptionally 10 l s^{-1}. The groundwater is not favoured for domestic consumption as water quality may be poor, with elevated concentrations of S and Fe sometimes providing the water with a sulphurous smell and an ochreous appearance in the vicinity of former coal workings.

Darnconner is situated on a gentle anticline which forms part of a faulted block of Middle Coal Measures, the bounding faults trending towards the west-north-west. The underlying Lower Coal Measures contain a similar cyclical lithological sequence to the Upper Coal Measures although the coal seams tend to be thinner. The Coal Measures generally dip towards the west where they become concealed beneath the volcanic rocks of late Carboniferous/Permian age and Permian sandstones of the Mauchline Basin some 8 km to the west of Darnconner.

Pumping records for former mines in the vicinity of Darnconner indicate that the Lugar Mine [NS58902164] was sump pumped from 29 m depth at 3 l s^{-1} for 16 hours per day, and the Highhouse Colliery in Auchinleck [NS550216] was pumped from 180 m depth yielding on average 1.5 l s^{-1}. These modest pumping rates suggest that the Coal Measures are only weakly fractured and that the groundwater storage and transport potential is small compared with the wetter mines in the Central and Lothians coalfields. This is borne out by a search of the BGS Wellmaster water borehole database for local groundwater users which reveals modest groundwater supplies from two boreholes only, one at Auchinleck [NS55262400] and one at Cronberry [NS60802260]. There are no records of any groundwater sources nearer to Darnconner other than these, which are 3.5 and 2.0 km from the site respectively.

Further to the west, the former Barony Mine [NS 5267 2185] worked the concealed Lower and Upper Coal Measures through the relatively barren Upper Coal Measures. The mine was pumped at a rate of 13 l s^{-1} from a depth of 528 m.

The tight nature of the Coal Measures in East Ayrshire indicates that the water table, although it may be locally influenced by any significantly dilated fracture or fracture set, will be shallow. The water table follows a subdued form of the surface topography and is likely to be only a few metres beneath ground level and near the surface at valley bottoms and beneath the local burns (engineered as well as natural). The exploratory pits at Darnconner indicate that the water table lies at greater than 3 m below ground level with the burn perched on till. The prevailing hydraulic gradient is to the west towards the Mauchline Basin (Figure 1). The overall dip of the strata, albeit much faulted and locally flexed, is also to the west.

The average annual effective rainfall for Cumnock is 662 mm (Table 1). The HOST database indicates a catchment BFI (Baseflow Index) in the region of 0.3, i.e. 30% of the long term flow derives from groundwater baseflow rather than direct runoff. The catchment estimate for the Lugar Water at Langholm [NS508217] is only 0.26. These values suggest that groundwater baseflow (which, if a balance is to be maintained over the long term, must equal groundwater recharge) amounts to effective annual rainfall (662 mm a^{-1}) multiplied by BFI (0.26) equals 172 mm a^{-1}. This estimate includes elements of very shallow flow such as soil interflow and the actual amount of water reaching the water table will be less than the derived figure. Local patches of gley soil and cover of till further inhibit recharge to the area. The likely infiltration rate is, nevertheless, small compared with the sandstone aquifer forming the Mauchline Basin where infiltration is likely to be at least 300 mm a^{-1}.

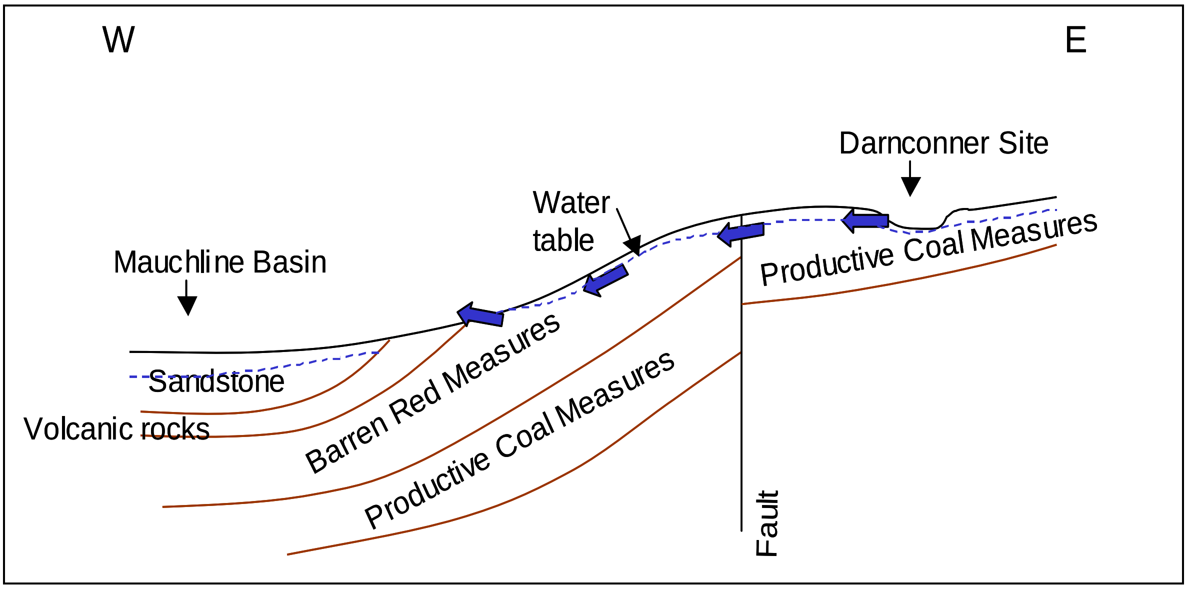

Figure 1. Schematic west east section through Darnconner

Groundwater flow from beneath the Darnconner site is roughly parallel to the surface drainage to the west, so that groundwater flows down-dip and down the hydraulic gradient to pass through the barren Upper Coal Measures towards the basalt which floors the Mauchline basin (Figure 1). Travel time through the weakly fractured rock driven by the low prevailing hydraulic gradient, is likely to be prolonged, 10s to 1000s of years, subject to accelerated flow via any available adits or former coal workings which may provide a by-pass flow path.

Bacteria, for the most part are attached to particulate matter and are not readily mobile. The potential for pathogen entry into groundwater is, therefore, small, and only likely if fracture by-pass type flow allows direct ingress to the water table (e.g. via undermined workings etc). Metals are bound to organic matter in the sludge and receiving soil and only become mobile if the pH falls and acid conditions are generated. Similarly, metals will only remain in solution in the groundwater if low redox and pH conditions are maintained away from the reclamation area,

There are few springs and seepages marked on 1: 10 000 scale topographical maps in the area. Ammonium and nitrite derived from the sludge will percolate down to the water table during periods of prolonged rainfall whilst the soil is at field capacity. However, provided the groundwater remains unconfined and is in contact with the atmosphere, nitrite may oxidise to nitrate. If the groundwater flows into a confined system in which free oxygen is not available, i.e. a reducing environment, denitrification may occur and gaseous N given off. This process is accelerated in the presence of denitrifying bacteria.

Mine abandonment data for the area indicate that the Darnconner opencast has not been undermined. It is unlikely that the mining and remaining adits developed from both the Highhouse and Lugar mines would greatly effect flow conditions beneath and down the hydraulic gradient (to the west) of the former Darnconner opencast site.

Table 1. Long-term effective rainfall at Cumnock

Month	Mean rainfall (mm)	Mean Potential evapotranspiration (mm)	Mean effective rainfall (mm)
January	126.5	12.8	113.8
February	69.1	14.2	55.0
March	105.6	31.3	74.3
April	57.0	49.6	7.5
May	54.1	81.9	0
June	59.6	77.1	0
July	72.5	80.9	0
August	93.4	66.5	26.9
September	113.6	46.5	67.1
October	125.9	29.4	96.5
November	124.7	18.0	106.8
December	126.0	11.2	114.7
TOTAL	1128	461	662

Assumption: actual evaporation ≈ potential evaporation

3 Darnconner – likely impact of biosolids recycling on groundwater

The impact of the proposed recycling of biosolids at Darnconner on groundwater is likely to be low to negligible. Although the water table is shallow, the key positive features of the site are:

1. Local infiltration is low <172 mm a^{-1}.
2. The Coal Measures are tight and fractures are not well developed.
3. The hydraulic gradient across the site is westerly and small.
4. There are few springs or groundwater users in the area – the three local farmsteads are all on mains supplies.
5. Transit times to groundwater discharge areas (towards the Mauchline Basin) are prolonged.
6. The groundwater is likely to remain in contact with the atmosphere and reduced N species may oxidise to nitrate.
7. The site has not been undermined and local mining is unlikely to provide accelerated by-pass flow-paths for groundwater flowing west from Darconner.

4 The assessment process

The process of assessment for Darnconner took the following steps:

1. Develop the 3-D geological framework for the area of interest using published geological maps and sections.
2. Assess degree of undermining using mine abandonment plans if necessary.
3. Review likely groundwater properties of rocks – intergranular and fracture flow/storage.
4. Assess local recharge potential.
5. Locate water table and prevailing hydraulic gradient.
6. Review local discharge points – baseflow and springs, throughflow to other aquifers.
7. Catalogue local groundwater users.
8. Create conceptual groundwater flow model as 2-D vertical section.
9. Assess travel times to discharge points.
10. Assess likely redox potential along flow path away from site to be reclaimed.
11. Provide overall assessment of likely impact to groundwater.

This procedure can be formalised within a flowchart and a tick-box procedure in order to maintain a standard approach to the groundwater impact assessment for any site (Table 2). Tick-box scores are shown for the Darnconner site assessment (Appendix 1).

A similar assessment was carried out for Heathland Forest [NS9959] where a broadly similar low impact score is attained (Appendix 1). A third site, Broken Cross [NS8537], is also assessed by way of contrast (Appendix 1). This site is a very large currently operational opencast site in Lanarkshire. The differences between the three sites are highlighted in Table 2.

The tick box procedure is providing appropriate and expected outputs. It is hard to conceive an opencast coal site beneath which a high groundwater impact is likely. Such a site would need to be:

1. Fractured and undermined with exposed adits.
2. Subject to a high effective rainfall.
3. Possess a shallow water table.
4. Traversed by a steep hydraulic gradient with direct unconfined flow paths to springs wells and boreholes, some of which are used for domestic supply.

The same basic hydrogeological conditions prevail at freestone and road stone quarries into bedrock such as dolerite, sandstone or limestone. The opencast tick-box assessment can be used in these situations. Many of the sites are likely to place groundwater at high risk simply because many of the sandstone quarries, e.g. Locharbriggs near Dumfries, have nearby groundwater users down gradient from the site, conversely dolerite quarries are commonly on elevated remnants of ground draining underground to nearby burns and rivers.

Conditions in sand and gravel pits, especially those that have been developed beneath the water table, are quite different, and the bedrock tick-box is no longer appropriate to assess the biosolids recycling impact on groundwater in these cases. For these situations a different set of questions need to be asked relating directly to likely pathways between the reclamation site and groundwater discharge or abstraction points. For the most part flow paths are short and discharge of nitrogen rich groundwater to surface is almost inevitable. These sites can be dealt with by considering the reclamation site as a hazard and evaluating the direction of groundwater flow from the site in relation to abstraction points and baseflow discharge zones that are down the hydraulic gradient and are likely to be at risk. As many possess a hydraulic connection to surface in the < 1 km range, few of these sites will be situated over groundwater that is either at moderate or low risk.

Table 2. Differences between the three example opencast sites

	Darnconner	**Heathland Forest**	**Broken Cross**
Geological Framework	Locally faulted and folded but not undermined	Locally faulted and undermined but no evidence of shallow workings intercepting near surface	Locally faulted, undermined and former adits exposed in opencast walls
Water Table	Water table >3 bgl, low hydraulic gradient away from site	Water table >3 bgl, low hydraulic gradient away from site	Shallow water table, site dewatering in progress, moderate hydraulic gradient away from site
Recharge Potential	Low	Moderate	Moderate
Discharge	Discharge and abstraction points are >3 km distant. No local groundwater users	Discharge and abstraction points are >3 km distant. No local groundwater users	Local springs and boreholes. Local groundwater users given replacement sources.
Likely Flow Paths	Shallow oxygenated flowpath away from site >5 km in length	Shallow oxygenated flowpath away from site >5 km in length	Shallow, but short in length, oxygenated flowpath away from site
Score	28 Low impact to groundwater	26 low impact to groundwater	17 moderate impact to groundwater
Comments	Derelict opencast site	Part reclaimed site	Operational opencast site

Verification of the assessment process can be undertaken by monitoring selected treated sites as demonstration facilities. The Darnconner site lends itself to this purpose as the existing ‘before’ situation can be evaluated prior to treatment and the subsequent impact, if any, can be measured. At Darnconner two monitoring boreholes placed at approximately 100 m and 500 m distant from the down-gradient perimeter of the treatment area would allow regular sampling and analysis for key determinands. However, such boreholes are dependent on access to neighbours land and may not always be feasible.

The boreholes need to penetrate the water table by about 10m and can be lined to firm bedrock with open hole below. Completed to not less than 100 mm internal diameter they should be surged and air lifted to clean the newly drilled holes. Sampling by a portable pump (Whale or similar) at 90 day intervals for a period of not less than three years will allow the baseline conditions to be established and any subsequent changes to be measured. Determinands should include NH_3, NO_2, NO_3, Cl, and total dissolved solids, plus the metals

Fe, Mn and Al. In addition a plate count for overall bacterial activity should be made every six months. Other desirable, but non-essential measurements include pH and dissolved oxygen, but as these are difficult to measure accurately in the field they are better included in a one off baseline analysis for all major and common trace elements and metals. The full analysis is again desirable but not essential to the monitoring procedure.

Monitoring at other selected sites should be along similar lines. However, it is only necessary to monitor two or three different site settings to verify the scorecard assessment. Other sites should include a lower score than Darnconner (e.g. approaching 15) and any sites that may score a medium impact should be routinely monitored.

In addition the HiRES electromagnetic dataset may provide a means of monitoring treated sites (see next section). However, as the timing of repeat flights is not within the control of the interested parties, this should only be considered as a support tool wherever suitable data have been gathered.

5 HiRES data

A BGS project HiRES (**Hi**gh resolution airborne **R**esource and **E**nvironmental **S**urvey) is the nationwide acquisition of new generation low-level, high-resolution airborne magnetic, radiometric and electromagnetic data. Parallel investigation of their application in a wide range of environmental, resource exploration and geological mapping programmes is ongoing.

Airborne geophysics is the remote measurement of Earth's physical properties from the air. These properties include electrical conductivity, radioactivity and magnetism and they can help to understand potential environmental hazards, the presence of certain resources and the underlying geology and structure. Advantages of airborne surveying include the rapid acquisition of multiple datasets, access over difficult terrain and non-invasive ground investigation which allows the targeting of potential problem areas for ground checking, and are therefore highly cost effective. The technique can be used for:

- Mapping and monitoring potential environmental hazards.
- Mitigation of geological hazards and risks.
- Characterising the surface and shallow sub-surface for land-use planning.
- Sustainable development of natural resources hydrocarbon and mineral exploration.

HiRES coverage is available only across the Darnconner tile (Figure 2). However, it just misses the 50 m flight line 'infill' across the Mauchline basin, and the 200 m flight line is relatively poor for small scale problems. The EM (electro-magnetic) data converted to half-space conductivities at high frequency (HF) averaging (say 0-30 m below ground level) (Figure 3) and at low frequency (say 0-60 m below ground level) (Figure 4) are shown using the same colour scale. The data reflect the occurrence and distribution of the Cl ion. The main central anomaly is largest at low frequency (LF) and would normally be interpreted as a powerline (e.g. 11 keV) moving from below ground to an overhead line as the conductivity anomaly stops part way down the track. The anomaly within the mine is of small amplitude (x2 background of the Coal Measures). It is greatest at HF (source near-surface). It most probably reflects waste material heaped along the line of the track to Darnconner.

The data illustrate the likely degree of increased mineralisation in the vicinity of the former opencast working. It would be valuable to look at a rerun of the EM data twelve months after treatment to see what degree of salinisation, if any, has occurred.

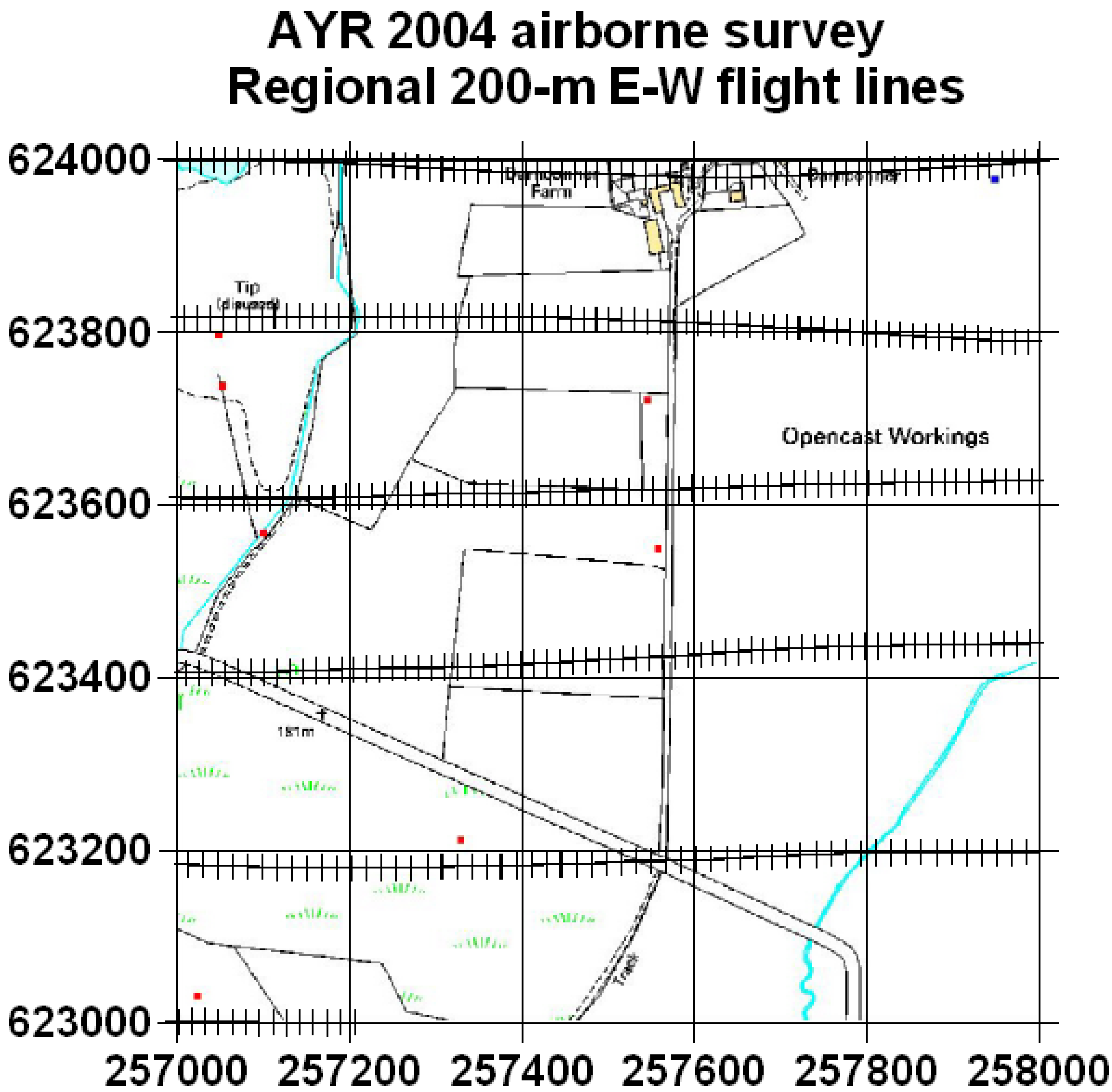

Figure 2. Darnconner site airborne survey

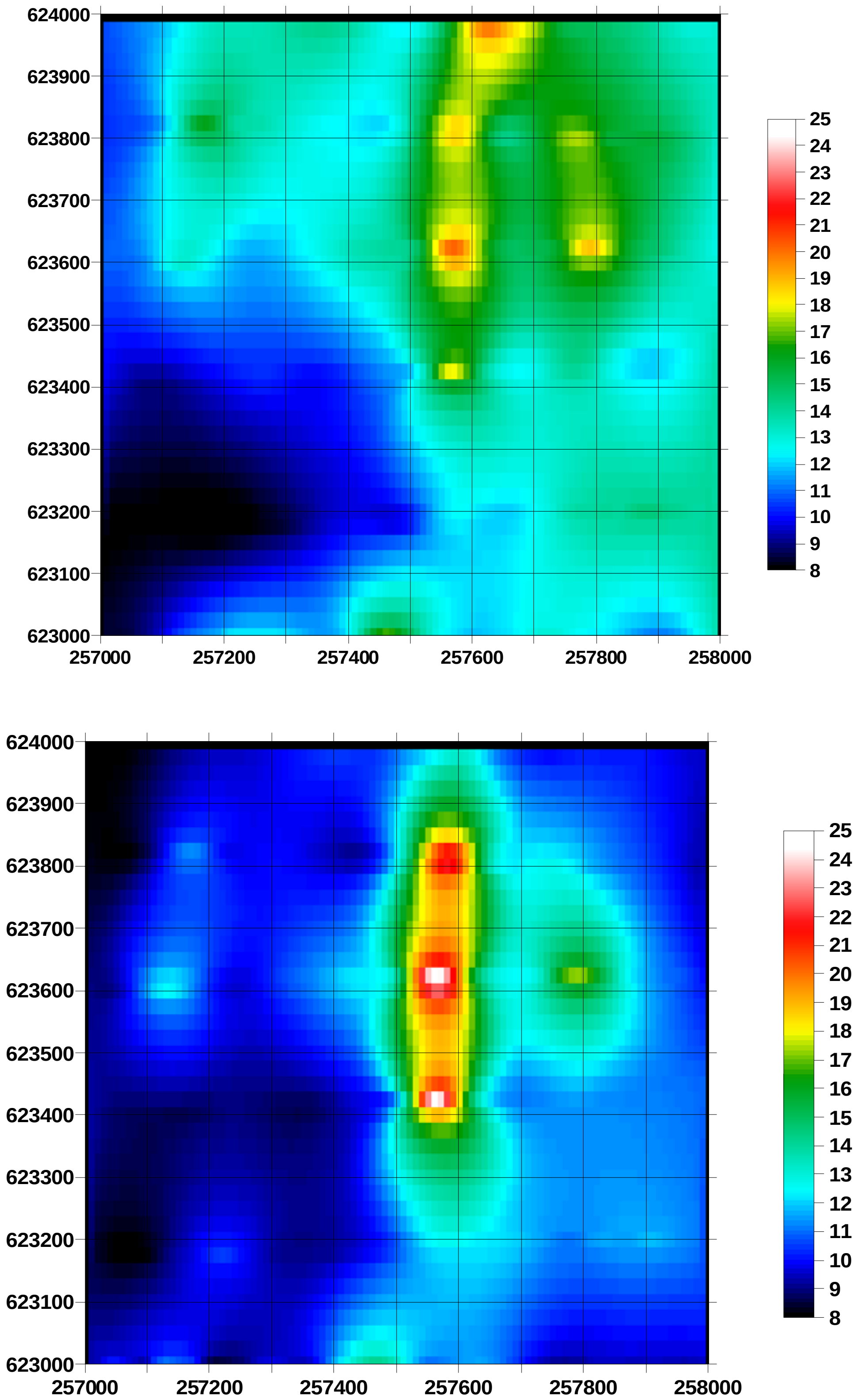

Figure 3. Darnconner NS5723 HF (top) and LF (bottom) conductivity 9mS m^{-1})

6 Conclusions

The risk of bacterial and metal contamination to groundwater is generally low unless there is a by-pass flowpath via a fracture or existing mine adit directly to the water table. The main pollution risk from biosolids spreading is nitrate derived from the oxidation of ammonium leaching to groundwater during periods of prolonged wet weather. Risk assessment hinges on the potential for transport of nitrogen species to groundwater, and a scorecard tick-box assessment system to assess the nature of the pathway and its potential to transport contaminants to the water table is presented and tested.

The scorecard assessment of impact on groundwater is based primarily on the potential for transport of nitrogen species to the water table and whether the groundwater remains in contact with the atmosphere down gradient from the site. The scorecard is equally appropriate for any bedrock configuration: Coal Measures, sandstone, limestone and dolerite quarries. It is not appropriate for pits in superficial material such as sand and gravel extraction sites.

The scorecard provides a standard approach to assessing impact. It requires a limited understanding of the site and the groundwater regime around and down gradient from the site. Data requirements are:

1. The 1: 50 000 published geological map.
2. HOST, BFI and effective rainfall.
3. Topography.
4. Mine abandonment locations and depth.
5. WELLMASTER borehole data.

The scorecard assessment depends on the preparation of a simple and schematic conceptual model of the groundwater flow regime derived from these data. This is best prepared as a schematic cross-section which is recorded as part of the procedure to ensure transparency. The assessment, although aided by and standardized by the scorecard, still requires technical and specialist input from a hydrogeologist in order to develop the conceptual model. It is possible also that the scorecard may require minor adjustment as more examples are assessed, but to date the scorecard appears robust and conclusive.

The HIRES geophysical data recently flown by BGS for parts of the Midland Valley allows Cl rich plumes to be detected beneath the trial flight paths completed to date. This may be a valuable tool with which to evaluate recycling sites in order to demonstrate groundwater impact for comparison with predicted impact. It is assumed that Cl concentrations will vary in proportion to N concentrations.

Appendix 1 Example scorecards

1. OPENCAST GROUNDWATER IMPACT ASSESSMENT SCORE CARD – for Darnconner

	Item		1	2	3	
1	GEOLOGICAL FRAMEWORK					
	Is the area faulted/folded?	Yes	***X***			No
	Is the area undermined?	Yes		***X***		No
	Are there adits visible in the opencast area?	Yes			***X***	No
2	WATER TABLE					
	What is the average depth to water	<3 m bgl		***X***		>20 m bgl
	What is the hydraulic gradient beneath and away from the site	> 0.01			***X***	<0.001
3	RECHARGE POTENTIAL					
	What is the BFI?	>0.50			***X***	<0.30
	What is the effective rainfall?	>300 mm a^{-1}		***X***		<150 mm a^{-1}
4	DISCHARGE *(if the answer is none, the score is three in each case)*					
	Are there springs down gradient from the site?	<1 km distant			***X***	>5 km distant
	Are there boreholes and wells in the vicinity and down-gradient?	<1 km distant			***X***	> 3 km distant and down gradient
	Are there any domestic users of groundwater?	<1 km distant			***X***	>3km distant
5	LIKELY FLOWPATHS TOWARDS THE DISCHARGE AREA					
	What is the length of the shallow unconfined flow-path away from the site?	<1km in length			***X***	>5 km in length
6	SCORES		***1***	***3***	***7***	*Weighted score:*
	WEIGHTED SCORES		x1 =***1***	x2 =***6***	x3 =***21***	*<15 high impact* *15-25 moderate impact*
	SUM OF WEIGHTED SCORES			***<u>28</u>***		*>25 low impact*

2. OPENCAST GROUNDWATER IMPACT ASSESSMENT SCORE CARD – for Heathland Forest

	Item		1	2	3	
1	GEOLOGICAL FRAMEWORK					
	Is the area faulted/folded?	Yes	***X***			No
	Is the area undermined?	Yes	***X***			No
	Are there adits visible in the opencast area	Yes			***X***	No
2	WATER TABLE					
	What is the average depth to water?	<3 m bgl		***X***		>20 m bgl
	What is the hydraulic gradient beneath and away from the site?	> 0.01			***X***	<0.001
3	RECHARGE POTENTIAL					
	What is the BFI?	>0.50		***X***		<0.30
	What is the effective rainfall?	>300 mm a^{-1}		***X***		<150 mm a^{-1}
4	DISCHARGE *(if the answer is none, then the score is three in each case)*					
	Are there springs down gradient from the site?	<1 km distant			***X***	>5 km distant
	Are there boreholes and wells in the vicinity and down-gradient?	<1 km distant			***X***	> 3 km distant and down gradient
	Are there any domestic users of groundwater?	<1 km distant			***X***	>3km distant
5	LIKELY FLOWPATHS TOWARDS THE DISCHARGE AREA					
	What is the length of the shallow unconfined flow-path away from the site?	<1km in length			***X***	>5 km in length
6	SCORES		***2***	***3***	***6***	*Weighted score:*
	WEIGHTED SCORES		x1 =**2**	x2 =**6**	x3 =**18**	*<15 high impact* *15-25 moderate impact*
	SUM OF WEIGHTED SCORES			***<u>26</u>***		*>25 low impact*

3. OPENCAST GROUNDWATER IMPACT ASSESSMENT SCORE CARD – for Broken Cross (Scottish Coal operational Opencast site)

	Item		1	2	3	
1	GEOLOGICAL FRAMEWORK					
	Is the area faulted/folded?	Yes	***X***			No
	Is the area undermined?	Yes	***X***			No
	Are there adits visible in the opencast area?	Yes	***X***			No
2	WATER TABLE					
	What is the average depth to water?	<3 m bgl	***X***			>20 m bgl
	What is the hydraulic gradient beneath and away from the site?	> 0.01		***X***		<0.001
3	RECHARGE POTENTIAL					
	What is the BFI?	>0.50		***X***		<0.30
	What is the effective rainfall?	>300 mm a^{-1}		***X***		<150 mm a^{-1}
4	DISCHARGE *(if the answer is none, then the score is three in each case)*					
	Are there springs down gradient from the site?	<1 km distant	***X***			>5 km distant
	Are there boreholes and wells in the vicinity and down-gradient?	<1 km distant		***X***		> 3 km distant and down gradient
	Are there any domestic users of groundwater?	<1 km distant			***X***	>3km distant
5	LIKELY FLOWPATHS TOWARDS THE DISCHARGE AREA					
	What is the length of the shallow unconfined flow-path away from site?	<1km in length	***X***			>5 km in length
6	SCORES		***6***	***4***	***1***	*Weighted score:*
	WEIGHTED SCORES		x1 =**6**	x2 =**8**	x3 =**3**	*<15 high impact*
	SUM OF WEIGHTED SCORES			***<u>17</u>***		*15-25 moderate impact* *>25 low impact*